Compaction of siliceous sediments – Implications for basin modeling and seismic interpretation

Øyvind Marcussen

Dissertation for the degree of Philosophiae Doctor (Ph.D.)

Faculty of Mathematics and Natural Sciences
Department of Geosciences
University of Oslo
Norway

Submitted: March 2009
Date of defense: May 27, 2009

Series of dissertations submitted to the
Faculty of Mathematics and Natural Sciences, University of Oslo
Nr. 855

ISSN 1501-7710

Cover: Inger Sandved Anfinsen.
Printed in Norway: AiT e-dit AS, Oslo, 2009.

Produced in co-operation with Unipub AS.
The thesis is produced by Unipub AS merely in connection with the
thesis defence. Kindly direct all inquiries regarding the thesis to the copyright
holder or the unit which grants the doctorate.

Unipub AS is owned by
The University Foundation for Student Life (SiO)

Preface

This thesis entitled “Compaction of siliceous sediments – Implications for basin modeling and seismic interpretation” has been submitted to the Department of Geosciences at the University of Oslo in agreement with the requirements for the degree of Philosophiae Doctor (Ph.D.) The work presented in this study was completed as part of a large research project funded by The Research Council of Norway within the PETROMAKS program (Program for Optimal Management of Petroleum Resources) entitled “Petrophysical properties of mudstones and sandstones and their seismic response”. The study is based on results from well log data in natural sediments from the Norwegian continental shelf. The derived compaction results have been integrated with results from experimental compaction studies performed within the same PETROMAKS project (Mondol, 2007). In addition, some of the work presented herein was completed in collaboration with a FORCE research project (Norwegian Sea Research Consortium) sponsored by ConocoPhillips, Gaz de France, Norsk Hydro and Statoil.

The thesis comprise of an introduction together with six individual papers. A brief scientific introduction to the topic, the main objectives, summary of the papers enclosed, and finally some concluding remarks are given in the introduction. Three of the papers within the thesis have been published while the remaining three have been submitted to international journals. The focus of the work is to understand the controlling factors for sediment compaction and how compaction affects rock physical properties in natural occurring sediments. The implications of the different compaction factors on techniques used for basin analysis and seismic interpretation have also been an important task during this study.

The first enclosed paper investigates natural compaction trends of Cenozoic mudstones from the northern North Sea basin in terms of mineralogy, provenance and facies. The implications of these compaction trends for basin modeling and seismic interpretation is also briefly discussed in this paper, while a more detailed analysis of the effect of varying physical properties in mudstones for such analysis is covered in the second and third paper. The second paper quantifies the uncertainties introduced in basin modeling by changing the compaction trends for mudstones. Paper 3 investigates the effect of physical properties in mudstones on the AVO signature of a siliceous hydrocarbon reservoir capped by mudstones with different mineralogical compositions. The compaction trend in a well defined lithology is studied in paper 4, while paper 5 and 6 relates compaction trends observed from well logs to the mineralogical composition and diagenetic development of Tertiary and Cretaceous mudstones from the Norwegian Sea.

Acknowledgements

First of all I would like to thank my supervisors Professor Knut Bjørlykke, Associate Professor Jens Jahren, and Professor Jan Inge Faleide for giving me the opportunity to start on this exciting study. Your advice, the discussion we have had, and your support helped me solve the challenges I have faced during my research. I am forever grateful. Thanks also to Professor Leiv-J Gelius who was very helpful during the work with seismic modeling and AVO. This work would never have been done without your contributions.

A special thank goes to all my present and former colleagues at the department. I appreciate all the discussions and contributions from Christer B. Peltonen, Brit I. Thyberg, Nazmul Haque Mondol, Manzar Fawad and Tom Erik Maast. My work has been greatly improved by your valuable input. In addition, I will also take the opportunity to thank Olav Antonio Blaich, Delphine Croizé, Audun Kjemperud, Edwin R. Schomacker and all my fellow students at our department. It has been a pleasure going to work, and I will always remember and appreciate this period of my life.

Financial support from the Research Council of Norway is greatly acknowledged. I would also like to thank industry members in the PETROMAKS project for their contribution. Isabelle Lecomte (NORSAR) is also greatly acknowledged for her excellent help in generating seismic modeling data needed for my work. I really appreciate the help from Michel Heeremans who was very helpful with all the practical aspects related to getting data for my database. Thanks also to Marit Sørlie and Kristin Rangnes from the library at the Department of Geosciences, you have always been very helpful.

Finally, my thanks go to my family who always supported me in all my decisions (good and bad). My deepest gratitude goes to the two most important persons for me, my wife Kristine and daughter Silja. I would never have been able to complete this work without your encouragement and support in all aspects of life.

Table of Contents:

List of Papers

Paper 1: Marcussen, Ø., Thyberg, B. I., Peltonen, C., Jahren, J., Bjørlykke, K. & Faleide, J. I., 2009, Physical properties of Cenozoic mudstones from the northern North Sea: Impact of clay mineralogy on compaction trends, AAPG Bulletin, 93, pp. 127-150.

Paper 2: Marcussen, Ø., Faleide, J. I., Jahren, J. & Bjørlykke K., submitted, Mudstone Compaction Trends in Basin Modeling: a study of Mesozoic and Cenozoic sediments in the northern North Sea, Basin Research.

Paper 3: Marcussen, Ø., Fawad, M., Gelius, L-J., Faleide, J. I. & Lecomte, I., submitted, AVO response as a function of cap-rock properties: a case study from the northern North Sea, First Break.

Paper 4: Marcussen Ø., Maast, T. E., Mondol, N. H., Jahren, J. & Bjørlykke, K., submitted, Changes in physical properties of a reservoir sandstone as a function of burial depth – the Etive Formation, northern North Sea, Marine and Petroleum Geology.

Paper 5: Peltonen, C., Marcussen, Ø., Bjørlykke, K. & Jahren, J., 2008, Mineralogical control on mudstone compaction: a study of Late Cretaceous to Early Tertiary mudstones of the Vøring and Møre basins, Norwegian Sea, Petroleum Geoscience, 14, pp. 127-138.

Paper 6: Peltonen, C., Marcussen, Ø., Bjørlykke, K. & Jahren, J., in press, Clay mineral diagenesis and quartz cementation in mudstones: The effects of smectite to illite reaction on rock properties, Marine and Petroleum Geology, doi:10.1016/j.marpetgeo.2008.01.021

Conference contributions

Abstract 1: Marcussen, Ø., Bjørlykke, K. & Jahren, J., 2006, Velocity and density versus depth in mudstones offshore Norway – Implications for basin modeling, presented as a scientific talk at the EUG, General Assembly, Vienna.

Abstract 2: Marcussen, Ø., Peltonen, C., Mondol, N. H., Bjørlykke, K. & Jahren, J., 2006, Velocity, density and porosity versus depth in mudstones, offshore Norway, presented as a scientific talk at the Force seminar: Physical Properties of Shales, Stavanger.

Abstract 3: Marcussen, Ø., Peltonen, C., Bjørlykke, K., Jahren, J., Faleide, J. I. & Mondol, N. H., 2007, Petrophysical properties of different mudstone lithologies as a function of progressive burial – Examples from offshore Norway, presented as a poster at the NGF Winter Meeting, Stavanger.

Abstract 4: Marcussen, Ø., Peltonen, C., Mondol, N. H., Bjørlykke, K. & Jahren, J., 2007, Physical properties in shales and mudstones versus depth and its implications for basin analysis, presented as a poster at the AAPG Annual Convention, Long Beach, Los Angeles.

Abstract 5: Marcussen, Ø., Thyberg, B. I., Jahren, J. & Bjørlykke, K., 2008, Well log derived petrophysical properties integrated with mineralogical data and experimental compaction for the understanding of mudstone compaction, presented as a scientific talk at IGC, Oslo.

Abstract 6: Marcussen, Ø., Maast, T. E., Mondol, N. H., Jahren, J. & Bjørlykke, K., 2009, Transition from mechanical to chemical compaction in sandstones- the Etive Formation, presented as scientific talk at the NGF Winter Meeting, Bergen

Introduction

This thesis presents a multidisciplinary study of sediment compaction utilizing well log data, mineralogical and chemical data from cutting samples, petrographic analysis of core samples and experimental compaction to understand how sediment compaction affects physical properties in natural siliceous sediments. Well log data provide important information about rock properties and their dependency with depth. By applying velocities, densities and porosities derived from well logs to study compaction trends as a function of sediment composition and burial history it is possible to increase the understanding of sediment compaction and diagenesis. The Norwegian continental shelf serves as a natural laboratory to study these processes since this an intensively studied area due to its great hydrocarbon potential. A dense well and seismic coverage enables us to investigate spatial changes in physical properties in relation to sediment composition, burial histories and seismic response.

The deposition and composition of sediments in a siliclastic system is controlled by factors such as the weathered and eroded host rock material, climate, sea level fluctuations creating accommodation space and facies variations. Once deposited, mudstones and sandstones have different response to burial which affect their physical properties in different ways. Mud and mudstones are generally much more compressible than sandstones providing very different rock building framework properties. Physical properties observed from well logs depend on bulk rock properties, and these will vary from a matrix-supported framework found in mudstones compared to a grain-supported framework found in sandstones. The initial textural, mineralogical, and chemical compositional differences between fine-grained and coarse-grained sediments will further have a great influence on the diagenetic evolution during progressive burial. A better understanding of the relationship between the initial composition, diagenetic development and rock physical properties in sedimentary rocks will provide important information when interpreting a sedimentary basin for commercial and academic purposes. Results obtained from this study provide important input data for general studies of sedimentary basins as well as for more detailed analysis such as reservoir characterization and quantitative seismic interpretation.

Scientific Background

Deposition and composition of siliceous sediments

Two-thirds of the world's sedimentary record consists of shales and mudstones (Schieber and Zimmerle, 1998), but the mineralogical composition of these sediments may vary considerably. The primary mineralogical composition plays an important role for the diagenetic development of mudstones during burial (Bjørlykke, 1998). Mudstones consist of a mixture of clay minerals and silt-sized particles (mainly quartz). The main clay minerals found in marine mudstones are smectite, kaolinite, illite and chlorite (e.g. Weaver, 1989), and this initial clay mineral assemblage holds important information about source area, depositional environment and paleoclimate (Weaver, 1989; Potter et al., 2005).

Kaolinite is a common constituent of well-drained soils in humid climates that may be eroded and re-deposited in siliceous sediments. Bjørlykke et al. (1986) also showed that authigenic kaolinite formed by meteoric water flushing in sand-rich sediments replacing K-feldspar and mica may be re-deposited in mudstones. Smectitic mudstones may be a result of alteration of volcanic sediments (e.g. Potter et al., 2005). These volcanic sediments may be from wind-blown ash-falls or the weathering product from a basic source rock (Pearson, 1990; Huggett and Knox, 2006). Smectite is also commonly found in desert environments where evaporation produces high silica saturations resulting in smectite formation. Detrital illite is generally associated with acid or metamorphic rocks, it may also be formed as an erosion product from sandstones. Detrital chlorite indicates physical weathering of igneous and metamorphic host rocks. Both illite and chlorite may be deposited in mudstones as erosion products of diagenetically formed illite and chlorite in sandstones. Detrital chlorite is an unstable mineral that will easily be chemically weathered, and the presence of this clay mineral in mudstones indicates a dry and cool climate (Karlsson et al., 1979; Rundberg, 1989; Pearson, 1990).

The proximal to distal relationship is also an important factor controlling the mineralogical composition of mudstones. Gibbs (1977) showed that coarse-grained clay minerals such as kaolinite is concentrated in proximal settings compared to finer-grained mudstones with a high smectite content. In addition, a higher content of silt-sized particles are likely to be found in mudstones located in a proximal position to the source area compared to more distal mudstones (Potter et al., 2005). The silt-sized particles found in mudstones are mainly quartz, feldspar, carbonates and organic matter. The presence of these constituents may greatly affect the rock physical properties of the sediments, for instance, carbonate cementation will lead to increasing velocities in mudstones due a framework stiffening (e.g. Bjørlykke and Høeg, 1997; Bjørlykke, 1999; Nygård et al., 2004).

Sandstones also have a wide range of mineralogical and textural compositions due to the same controlling factors as for mudstones (provenance, facies and depositional environment). Rock framework minerals in sandstones are most commonly quartz, but significant amounts of feldspars, clay minerals, rock fragments and carbonate are usually important constituents (e.g. Boggs, 1995). It has been shown that the composition of sandstones may be tied to the tectonic setting of the source area (Dickinson et al., 1983). Reworked sandstones may for instance be dominated by quartz compared to feldspar. Initial footprint such as mineralogical and chemical composition of a sandstone together with textural properties such as grain-size, pore and grain geometries, sorting, clay content and the number of grain contacts are, as for mudstones, all important aspects controlling the diagenetic evolution with depth in sandstones (e.g. Giles, 1997).

Sediment compaction

Sediment compaction is the process that reduces sediment volume during progressive burial. In siliciclastic sediments mechanical compaction is the dominant process at shallow depth while chemical compaction becomes increasingly important as temperatures are increased during burial (e.g. Bjørlykke et al., 1989; Bjørlykke, 1998). These main compaction processes are fundamentally different when it comes to their controlling factors (Bjørlykke et al., 1989; Bjørkum et al., 1998), but together they drive the sedimentary rocks towards higher mechanical and thermodynamical stability (Bjørlykke, 1999).

Mechanical compaction is controlled by the effective stress generated by the weight of the overburden and starts immediately after deposition. The physical processes involved during mechanical compaction include sliding, reorientation, bending of ductile grains and grain crushing. If the pore fluid is inhibited to escape from the rock during compaction or gas is released from source rocks the pore pressure may increase (Swarbrick and Osborne, 1998). This pore pressure increase will reduce the effective stress, thus retarding mechanical compaction. In siliceous sediments mechanical compaction is important at depths corresponding to temperatures lower than 60-80˚C, at greater depths and temperatures chemical compaction becomes the important porosity reducing process (e.g. Bjørlykke et al., 1989; Bjørlykke, 1998). Chemical compaction is controlled by time and temperature and includes dissolution and precipitation of minerals (Murphy et al., 1989; Walderhaug, 1994b, 1996, 2000). This process leads to a stiffer rock that becomes mechanically pseudo-over-consolidated and therefore insensitive to the effective stress (Bjørlykke and Høeg, 1997; Storvoll et al., 2005; Bjørlykke, 2006). Quartz cementation is the main chemical compaction process in sandstones (Bjørlykke et al., 1986; Ehrenberg, 1990; Walderhaug, 1994b), with quartz being dissolved along stylolites and re-precipitated on quartz grains as cement (Oelkers et al., 1992, 1993; Walderhaug, 1994a; Bjørkum, 1996; Oelkers et al., 1996; Walderhaug, 1996). Chemical compaction in mudstones varies depending on the initial clay mineralogical composition. One important diagenetic reaction in mudstones is the transformation from smectite to illite that occurs at temperatures between 60-100˚C (Hower et al., 1976; Boles and Franks, 1979; Pearson and Small, 1988; Pearson, 1990; Bjørkum and Nadeau, 1998; Nadeau et al., 2002; Thyberg et al., 2009). In addition to illite formed by alteration of smectite, authigenic illite could be the result of alteration of K-feldspar and kaolinite at approximately 130˚C (Bjørlykke et al., 1986; Ehrenberg and Nadeau, 1989). Authigenic chlorite may also be formed by diagenetic transformation of smectite and kaolinite (Hurst, 1985; Primmer and Shaw, 1987).

Compaction trends in siliceous sediments

Variations in physical properties in siliceous sediments with depth/temperature have in the literature been intensively studied due to its great importance for the petroleum industry and to increase the general academic understanding of sediment compaction. A large range of compaction trends have been published for siliceous sediments as a response to the various compaction processes acting in sedimentary basins (e.g. Giles, 1997; Mondol et al., 2007 and references therein). When considering a well defined lithology, the velocity and density will always increase and porosity will always decrease with increasing burial due to mechanical and chemical compaction (e.g. Giles, 1997). If inversion of these properties is observed with increasing burial depth the only explanation can be that there is a change in lithology. The compaction trends observed for siliceous sediment therefore reflect differences in initial sediment composition and diagenetic histories. Experimental compaction studies provide important information about mechanical compaction as a function of sediment composition and sorting (e.g. Chilingar and Knight, 1960; Chuhan et al., 2002, 2003; Mondol et al., 2007, 2008a), but due to low kinetic reaction rates in siliceous sediments the effect of chemical compaction on velocity, density and porosity is difficult to simulate in the laboratory. Natural compaction studies are therefore of great importance in order to fully understand the total diagenetic evolution of sedimentary rocks.

Porosity

Empirical porosity/depth trends have been published in the literature by the application of experimental and natural data. Linear porosity/depth trends have been applied by many authors to describe the porosity/depth development in restricted depth intervals (e.g. Galloway, 1984; Giles et al., 1992; Ramm and Bjørlykke, 1994). This may in some cases be a reasonable description of porosity variations with depth. However, linear trend eventually implies negative porosities. Exponential compaction trends are therefore frequently used to describe porosities in mudstones and sandstones (e.g. Sclater and Christie, 1980). This type of compaction curve does not consider the differences between mechanical and chemical compaction and is based on the assumption that the loss in porosity is driven by the vertical effective stress (Giles, 1997). Chemical compaction, which is controlled by temperature, may lead to a change in the porosity/depth relationship. One single exponential compaction curve may therefore fail to describe the porosity/depth relationship of a given lithology.

Both data from natural compaction studies and experimental work show that mudstones have initial porosities of about 70-80% which are rapidly reduced during early burial while sandstones have lower initial porosities of 45-50% and retain higher porosities during the initial stages of burial (Velde, 1996; Giles, 1997; Chuhan et al., 2002; Potter et al., 2005; Mondol et al., 2007) (Figure 1).

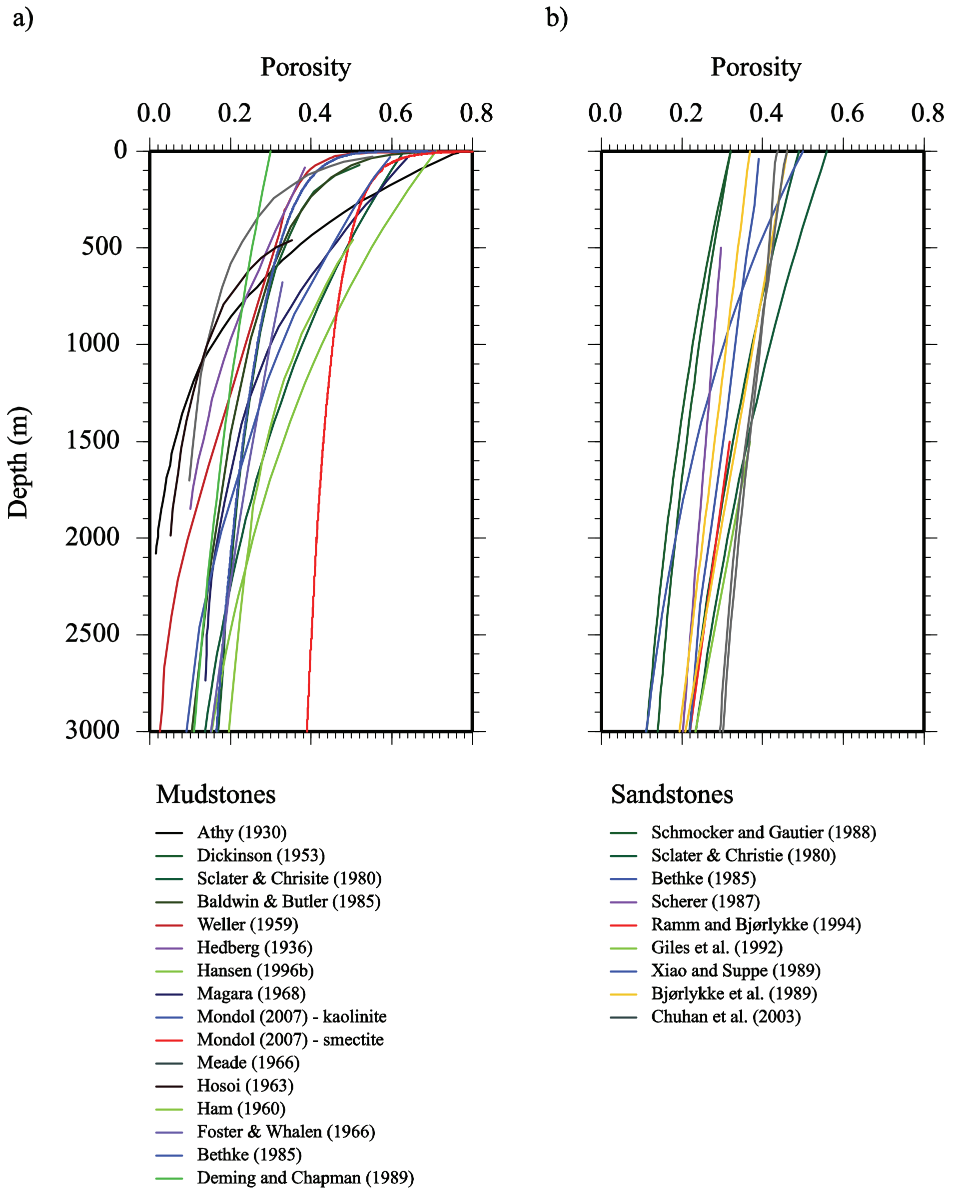

Figure 1. Published porosity/depth trends for shales (a) and sandstones (b).

A compilation of published porosity/depth curves for argillaceous sediments clearly demonstrates the wide range of possible porosities found for shales and mudstones at the same burial depth (Figure 1a). The rapid loss of porosity during shallow burial evident in many of the published curves is due to an open framework consisting mainly of clay mineral platelets in newly deposited mudstones. This open structure will relatively easily collapse during the initial stages of burial causing a rapid early porosity reduction. Experimental compaction studies of clay mineral aggregates have shown that more than 50% of the total porosity reduction occurs at stresses lower than 1MPa (~100 meter burial) (Mondol et al., 2007). The experimental results also demonstrated the importance of clay mineralogy on the compaction trends, with large differences in porosities between kaolinite and smectite mixtures. This relationship has also been observed in natural compaction studies combining mineralogy and well log data (Rundberg, 1989; Thyberg et al., 2000).

Due to its great potential as hydrocarbon reservoir rocks the porosity distributions in sandstones have been intensively studied in the literature (e.g. Giles et al., 1992; Ramm, 1992; Ramm and Bjørlykke, 1994). Prediction of porosities with depth in sandstones are linked to burial history, effective stress, temperature/depth, and mineralogy and texture (e.g. Bjørkum et al., 1998). The initial porosity and early compaction is controlled by mineralogy, sorting and clay content (Giles, 1997; Chuhan et al., 2002) and is therefore highly influenced by sedimentary facies and provenance (e.g. Atkins and McBride, 1992). In contrast to mudstones, a relatively dense packing of rigid grains found in sandstones will not collapse under the weight of the overburden, and the early porosity reduction is less than for mudstones (Figure 1b).

Velocity

The velocity distribution in siliceous sediments is also strongly dependent of the mineralogical and textural composition. Natural compaction studies show that very different velocity/depth trends are present within a sedimentary basin, and these variations are closely linked to the initial sediment composition (e.g. Rundberg, 1989; Thyberg et al., 2000; Storvoll et al., 2005). Velocity/depth trends are important for pore pressure prediction (e.g. Herring, 1973), depth conversion of seismic data (e.g. Al-Chalabi, 1997), estimates of uplift (e.g. Bulat and Stoker, 1987) and for identifying lithologies on seismic section. Several studies have related velocity to external and internal factors in sedimentary rocks. Wyllie et al. (1956; 1958) found a relationship between velocities and porosities in sandstones by experimental work, Gardner et al. (1974) related velocities to densities, while Nafe and Drake (1957) related velocity to the overburden thickness for marine sediments based on seismic refraction data. Other factors such as contact stiffness, clay content, clay mineralogy, pore pressure, pore geometry, pore fluid and sorting strongly affects the sonic velocities of sedimentary rocks (Mindlin, 1949; Gassmann, 1951; Biot, 1955; Chilingar and Knight, 1960; Winkler, 1983; Han et al., 1986; Marion et al., 1992;

Mondol et al., 2007). Experimental compaction studies may isolate each of these effects, but velocities found in well logs and from seismic data is a combination of several of these factors making it difficult to separate the contribution from each effect in natural compaction studies.

While the effective stress controls the compaction and velocity distribution in siliceous sediments at shallow depth, chemical compaction is very important for the velocity/depth distribution in a sedimentary basin. Precipitation of cement during the chemical alteration of sandstones and mudstones during burial strongly affects velocities. Cement on grain contact in sandstones will lead to a much stiffer material because cement will prevent movement between the individual particles (Winkler, 1983; Bernabé et al., 1992; Vernik and Nur, 1992; Dvorkin et al., 1994). This leads to an increase in velocities that is evident from well log data (e.g. Storvoll et al., 2005). Cement at grain contacts will not be applicable to mudstones because these sediments are matrix supported in contrast to a grain supported framework in sandstones. However, recent studies of quartz cementation in mudstones have show that an interconnected micro-quartz network and aggregates in the clay matrix may cause a stiffening that leads to increasing velocities (Thyberg et al., 2009).

Implications of compaction trends

Basin modeling

Despite the variations in compaction trends some curves have been adapted as standard compaction curves which are used for many basin analysis purposes. Giles (1997) analyzed several of the published porosity/depth for sandstones and mudstones and came up with average compaction curves for different lithologies. Such analysis may be used in areas with small amounts of data, but possible deviations from the applied standard compaction curve needs to be kept in mind when extracting porosity information in a sedimentary succession. The compaction curves for sand and shale described by Sclater and Christie (1980) from the North Sea have been used as a standard compaction trend in many studies along the Norwegian continental shelf (e.g. Fjeldskaar et al., 1993; Christiansson et al., 2000; Odinsen et al., 2000a, 2000b; Fjeldskaar et al., 2003, 2004). Kyrkjebø (1999) used the existing empirical porosity/depth relationships and found that there was only small differences in decompacted sediment thicknesses between the sand and shale compaction curves of Sclater and Christie (1980). However, from the published compaction curves of argillaceous sediments (Figure 1a) it is evident that there are larger differences between mudstone compaction curves than what is found by comparing mudstones with sandstones. To constrain the porosity/depth relationship in mudstones is especially important because mudstones dominate the sedimentary successions (Hermanrud, 1993), but quantitative studies of the uncertainty related to mudstone compaction trends in basin modeling is an unaddressed issue in the literature.

Basin modeling results are affected by the applied compaction trends in several ways. Velocity/depth trends may be used for depth conversion, and porosity/depth trends are used for geometrical restoration by decompaction and structural restoration. Considerable variations in the geometry of a sedimentary basin may therefore be found by applying different compaction trends. The large porosity variations found at the same burial depth for mudstones will also greatly affect the weight of the sedimentary column which has implications for isostatic subsidence estimates. Backstripping uses the calculated isostatic subsidence to estimate the contribution of tectonic subsidence by subtracting isostatic from total subsidence (Watts and Ryan, 1976; Steckler and Watts, 1978; Watts et al., 1982; Hendrie et al., 1993; Kusznir et al., 1995; Nadin and Kusznir, 1995; Roberts et al., 1998; Allan and Allan, 2005). The "observed" tectonic subsidence is then used to predict stretching factors which are used as input to calculate paleo heat flow development during rifting. Finally, the obtained results from the subsidence analysis may be used together with thermal properties of the sediments and kinetic source rock properties to study the paleotemperature history and the maturation of hydrocarbons within a basin.

Uplift and exhumation

Porosity/depth and velocity/depth trends have been used to quantify the amounts of uplift and erosion (e.g. Hillis, 1995; Hansen, 1996a; Densley et al., 2000). The fundamental assumption when applying this technique is that compaction is an irreversible process. This implies that porosities and velocities resemble the maximum burial depth (effective stress) the sedimentary rock has experienced. Higher velocities or lower porosities than expected for a certain depth of burial can therefore be used to predict the difference between present day and maximum burial depth. It is important to consider hydrostatically pressured sediment when applying this technique because sediments with high pore pressure have higher porosities and lower velocities than expected for the given effective stress.

Pore pressure prediction

Abnormal pore pressures are found in rocks in sedimentary basins worldwide. Dickinson (1953) was one of the first to study abnormal pressures using data from the Gulf of Mexico, and proposed incomplete dewatering as an explanation for the high pore pressures encountered. Several other mechanisms, such as thermal effects (Barker, 1972), the smectite to illite transformation (Powers, 1967; Bruce, 1984), and osmosis (Marine and Fritz, 1981) have been proposed to result in overpressure generation. However, the most common explanation is disequilibrium compaction providing higher than expected porosities (Bredehoeft and Hanshaw, 1968; Summa, 1993; Swarbrick and Osborne, 1998). Hottmann and Johnson (1965) showed that abnormal pressures could be inferred by interpreting wireline logs, and Hermanrud et al. (1998) suggested that porosities derived from sonic and resistivity logs are directly related to fluid pressures and may be used to predict high pore pressures. This technique has been adapted by many authors to predict the presence of areas with high abnormal pressures along the Norwegian continental shelf (e.g. Herring, 1973; Reemst et al., 1996; Japsen, 1999). Recently, Mondol et al. (2008b) combined compaction trends from experimental compaction with well log data from the North Sea and Vøring Basin as a tool for pore pressure prediction in mechanically compacted sediments. Pennebaker (1968) and Reynolds (1970) proposed that it was possible to detect areas of abnormal pressure by analyzing acoustic velocities from seismic data. However, Teige et al. (2007) showed that low velocities in shales related to overpressure may be found in mudstones without higher than expected porosities, and stated that the factors affecting acoustic velocities must be known in order to accurately predict pore pressure from seismic data.

Seismic sequence stratigraphy

Sequence stratigraphy is a powerful tool to predict facies distributions and depositional environments and is commonly applied by the petroleum industry for exploration purposes. This methodology applies the concept of correlating sedimentary strata bounded by unconformities and/or their correlative conformities (Vail et al., 1977; Vail, 1987; van Wagoner et al., 1988). Seismic stratigraphy was developed by the Exxon Production Research Company (Vail and Sangree, 1971; Vail, 1975; Vail et al., 1977) and is defined as "the study of stratigraphy and depositional facies as interpreted from seismic data" (Mitchum, 1977). Mitchum et al. (1977b) defined depositional sequences boundaries on seismic data as surfaces defined by onlap terminations, truncation terminations and downlaps induced by global sea level changes. Later studies along the Norwegian continental shelf have shown that also the tectonic development have a strong impact on the deposition of the various seismic sequences (Jordt et al., 1995, 2000; Faleide et al., 2002). Within the depositional sequences, seismic facies was defined as mappable units composed of groups of reflections characterized by the reflection configuration, continuity, amplitude, frequency, or interval velocities different from adjacent units (Mitchum et al., 1977a). These parameters are very sensitive to changes in physical properties (acoustic impedance) within the sedimentary rocks, thus an increased understanding of these parameters may help the interpretation of seismic data within a seismic stratigraphic framework. Especially the large range in physical properties found for mudstones may provide new insight to seismic stratigraphy.

Quantitative seismic interpretation

The analysis of seismic data in order to extract information about rock properties is a key to successfully describe subsurface rocks in terms of lithology, porosity, fluid content, permeability etc. This is important when searching for hydrocarbons because it may be possible to interpret a change in seismic response as function of geological processes. Rock physics may, when combined with a geological model, provide an important link between the interpretation of seismic attributes and geological properties. Many rock physical models relate velocity and impedance to mineralogy and porosity in order to interpret porosity and lithology. The Voigt (1910) and Reuss (1929) upper and lower bounds, respectively, represents the simplest models, but many models for calculating elastic bounds have been proposed to describe the elastic properties of rocks (e.g. Hashin and Shtrikman, 1963). Velocity/porosity trends have in sedimentary rocks been shown to be very dependent on the diagenetic history of the rock during burial (e.g. Dvorkin and Nur, 1996). These trends tend to be different in sedimentary rocks where porosity is controlled by diagenesis (diagenetic trends) compared to sediments in which the porosity is controlled by variations is sorting and clay content (depositional trends) (Avseth et al., 2005). The interpretation of seismic properties may therefore be done with a higher degree of certainty when more information about mineralogy and texture are added to the analysis. Many rock physic models for clean sands (Dvorkin et al., 1994; Dvorkin and Nur, 1996; Avseth et al., 2000), shales and shaly sandstones (e.g. Marion et al., 1992; Dvorkin and Gutierrez, 2002) have been developed for this purpose. However, sedimentary rocks with similar porosities may have different velocities which make it difficult to distinguish different lithologies and pore fluids. By combining compressional (V_p) and shear wave (V_s) velocity this may be possible because the non-fluid effects on V_p and V_s are similar (Castagna, 1993; Avseth et al., 2005).

Amplitude variations on seismic data have proven to be an important exploration tool for oil companies. To use amplitudes to predict the occurrence of hydrocarbons from seismic data was first proposed by Hammond (1974) who showed that a bright spot on a seismic section could indicate gas or oil. Amplitude versus offset (AVO) was later introduced by Ostrander (1984) who showed that hydrocarbons in a sandstone lead to varying amplitudes as a function of offset between source and receiver. Since then AVO analysis has become an important tool for the petroleum industry in their search for oil and gas because the amplitude variations on seismic data can be physically explained by rock properties (Avseth et al., 2005). The presence of such features on seismic data may also represent variations in lithology, rock physics and petrophysics are therefore needed to confirm that the amplitude anomalies are due to fluid effects rather than a change in lithology.

Main objectives

By combining well log data with mineralogical and chemical data, petrographic evidence and experimental compaction it is possible to interpret regional variations in these properties (that reflect changes in lithology, mineralogy and burial history) in terms of sediment composition, facies and provenance. Compaction trends provide information that will assist and improve the interpretation of seismic data and results from basin modeling. This thesis therefore investigates the controlling factors on compaction trends for siliceous sediments and their implications for basin modeling and seismic interpretation.

Specific objectives

- To analyze log data from mudstones and sandstones and mineralogical data from cutting samples and cores to describe compaction trends in relation to mineralogy, provenance, pore pressure and diagenetic development (Papers 1, 4 & 5). The petrophysical properties in well defined lithologies were studied by combining well logs with mineralogical and chemical data, petrographic analysis and experimental compaction (Papers 4 & 6).

- To quantify the effect of different mudstone compaction trends in basin modeling. This was done along an intensively studied transect from the northern North Sea basin where uncertainties in other input parameters are well constrained (Paper 2).
- The large variations found in densities and velocities in mudstones provide a large range of physical properties in cap-rocks to potential hydrocarbon reservoirs. The sensitivity of varying cap-rock properties of the AVO response on a reservoir sandstone was investigated (Paper 3).

Main Findings

This thesis consists in addition to the introduction of six individual scientific papers. The following section gives a short overview of the purpose and main findings and the conclusions presented in the papers.

Paper 1

Physical properties of Cenozoic mudstones from the northern North Sea: Impact of clay mineralogy on compaction trends (AAPG Bulletin)

A statistical analysis of petrophysical properties of Cenozoic mudstones in 42 well logs from the northern North Sea basin demonstrated that there are considerable variations in velocities and densities as a function of burial depth. This dataset was used to document changes in rock physical properties as a function of stratigraphy, lithology and clay mineralogy. By combining petrophysical properties from the well logs with clay mineralogical data (Berstad and Dypvik, 1982; Rundberg, 1989; Thyberg et al., 2000) it was clear that the primary mineralogical composition controlled by provenance controls the compaction trends for mudstones. This agreed well with depositional models for the northern North Sea (Jordt et al., 1995, 2000; Faleide et al., 2002). Velocity/depth trends and porosity/depth trends are important input parameters for basin modeling and seismic interpretation, and the results from this paper provide important information that may be used as input when analyzing mudstones in a sedimentary basin (papers 2 and 3).

The main findings and conclusions were:

- The large range of physical properties found for the Cenozoic mudstones is a result of the initial mineralogical and textural composition of mudstones. This initial composition may vary significantly throughout a sedimentary basin due to changes in provenance and facies.

- The smectite content is the most important factor controlling the velocity and bulk density distribution with depth for Cenozoic mudstones in the northern North Sea basin. The high smectite content within Eocene and Oligocene mudstones from the northern North Sea cause low velocities and bulk densities. High pore pressure in smectite-rich mudstones may partly explain the low values due to a retarded mechanical compaction because of a reduced effective stress.
- Increasing velocities with depth in the smectite-rich Paleocene interval may reflect a thermal breakdown of smectite to illite and quartz. A correlation between high resistivities and high velocities may be caused by fresh water released by this diagenetic reaction, but variations in the primary mineralogical content can also explain the increased velocities and restitivites.
- The coarse-grained and poorly sorted Miocene-Pleistocene mudstones compact more at low stresses and have higher velocities and densities than smectite-rich mudstones. There are also regional variations in compaction trends for this unit that correlates with two different depocentres sourced from different provenance areas.
- Depth conversion, basin modeling and seismic interpretation require information about how velocities, densities and porosities vary with depth. The large variations found in these properties in Cenozoic mudstones from the northern North Sea show that mudstone heterogeneity should be considered during such analysis rather than applying default shale properties. Both seismic facies and the AVO response of a hydrocarbon filled sand is influenced by mudstone properties.

Paper 2

Mudstone Compaction Trends in Basin Modeling: a study of Mesozoic and Cenozoic sediments in the northern North Sea (submitted to Basin Research)

Rock physical properties of sedimentary rocks are important input parameters to basin analysis when modeling the subsidence histories and the paleotemperature development of sedimentary basins. Mudstones and shales have normally been considered as a uniform lithology during modeling of sedimentary basins and have been assigned exponential or linear compaction trends. However, both experimental compaction (Mondol et al., 2007) and detailed studies of natural mudstones (e.g. Rundberg, 1989; Thyberg et al., 2000; Peltonen et al., 2008) have shown that there are large variations in compaction trends between different mudstone lithologies as described in papers 1,5 and 6.

This paper presents for the first time a detailed sensitivity analysis on the effect of varying compaction trends in mudstones for results obtained from basin modeling. This effect was tested on the post-rift succession along a well studied transect from the northern North Sea basin (Christiansson et al., 2000; Odinsen et al., 2000a, 2000b; Fjeldskaar et al., 2004; Rüpke et al., 2008). Different porosity/depth trends with smectitic and kaolinitic properties derived from experimental compaction (Mondol et al., 2007) with varying thermal conductivities was applied to the Cenozoic succession along the transect. Results were compared to those obtained using a standard compaction curve normally applied to the North Sea (Sclater and Christie, 1980) with standard thermal properties.

The main findings and conclusions were:

- There are great variations in physical properties in mudstones as a function of clay mineralogy. Well log data from the northern North Sea basin show that smectite-rich mudstone may have ~20% higher porosities than kaolinite-rich sediments at the same burial depths. This study shows that the clay mineralogical composition of mudstones have significant implications for the modeling of basin geometries, subsidence and thermal histories of sedimentary basins.
- Decompaction and geometrical restoration is important outputs from basin modeling providing information about the basin geometry through time. Different sediment thickness through time was observed when comparing a standard compaction curve for shale with porosity/depth trends derived for kaolinitic and smectitic mudstones. Maximum differences from the standard compaction curve of 10-15% in decompacted sediment thickness for the Cenozoic succession was observed along the modeled transect. This shows that laterally varying mineralogical composition and pore pressures have the potential of causing differential compaction and tilting of a sedimentary basin.
- One important aspect of basin modeling is to get subsidence estimates in order to model the basin evolution with respect to its hydrocarbon potential. The differences in isostatic subsidence obtained using the smectite/kaolinite porosity/depth trends compared to the standard shale compaction curve was found to be 2.3-4.6% along the northern North Sea transect. Corresponding differences in tectonic subsidence of ~3-8% gave rise to variations of up to 7.8% in stretching factors that will further affect the modeled heat flow into the basin during rifting.

- To get reliable estimates of the temperature development from basin modeling assumptions about the thermal properties within the sedimentary layers are essential. Differences of 20ºC in present day temperatures of an Upper Jurassic source rock was found by varying the thermal conductivites within the Cenozoic sediments along the modeled profile. This has implications for the calculated petroleum generation and is an important parameter to constrain when analyzing a sedimentary basin.

Paper 3

AVO response as a function of cap-rock properties: a case study from the northern North Sea (submitted to First Break)

The impact of clay mineralogy on petrophysical properties in mudstones described in papers 1, 5, and 6 may potentially have large implications for the interpretation of amplitude variations with offset on seismic data. This paper presents a study on the effect of varying petrophysical properties in mudstones on the AVO response of a gas-filled sandstone reservoir. Based on well log data from 11 wells and a seismic sequence stratigraphic interpretation along a seismic line in the northern North Sea (Faleide et al., 2002) a detailed geological model across a Paleocene oil/gas field was used as input to generate synthetic seismic data. Synthetic data with cap-rock properties resembling a smectite-rich and a kaolinite-rich mudstone was generated together with a reference model to study the effect of clay mineralogical content in cap-rocks on the AVO response of a sandstone reservoir. Results from this study show that the initial composition of cap-rocks greatly affects their elastic properties, and these variations proved to have significant implications for the interpretation and classification of AVO attributes.

The main findings and conclusions were:

- The understanding of cap-rock properties is very important for the interpretation of the seismic response of a sandstone reservoir. Variations in the initial mineralogical composition give rise to very different velocities and densities at the same burial depth. These variations have significant implications for the prediction of AVO classes. The AVO signature changed from a class I to a class II AVO sand by changing the mineralogical content in the cap-rock from a smectite dominated to a kaolinite dominated mudstone. The results presented in this study show that not only the elastic properties of a reservoir unit affects the interpretation of seismic amplitude variations.

- With the application of a geological model it is possible to more properly extract physical properties for a cap-rock than applying default shale values. Input of realistic cap-rock properties will improve estimates of AVO background trends, and therefore improve the interpretation of AVO attributes in terms of fluid content and lithology.

Paper 4

Changes in physical properties of a reservoir sandstone as a function of burial depth – the Etive Formation, northern North Sea (submitted to Marine and Petroleum Geology).

This paper presents a detailed investigation of how the compaction trend of a relatively homogeneous lithology varies with depth and temperature. The shallow marine Etive Formation of Middle Jurassic age from the northern Viking Graben was chosen for this purpose. In the study area the Etive Formation is buried from 1600-4000 meter below sea floor which enabled us to study the effect of burial diagenesis on rock properties. The Etive Formation sandstones are beach/barrier deposits and consist mainly of well sorted, medium sized, sand. Petrophysical properties from 21 wells were analyzed and compared with experimental compaction of loose Etive sand together with petrographical analysis of 23 thin sections. Reservoir characterization, basin modeling and quantitative seismic interpretation require information about how rock physical properties change with depth This study, which combines well log data with experimental compaction and petrographic analysis provide important information on the dependency on various diagenetic processes on rock properties in sandstones.

The main findings and conclusions were:

- In a single, well defined lithology such as the Etive Formation the velocity and density always increase with increasing burial depth and temperature.
- At burial depths corresponding to temperatures lower than 70-80˚C (<2000-2500 m in the northern North Sea) there is a good agreement between velocities, densities and porosities derived from well logs and values found by experimental compaction. This indicates that the vertical effective stress generated by the weight of the overlying sediments is the main porosity reducing agent at shallow depth.
- From about 2000 meters (>70˚C) there is a break in the velocity-depth gradient that may represent the onset of chemical compaction, mainly by quartz cementation, as observed by the petrographic analysis. This gradient change is observed by a relatively marked increase in velocities without a corresponding increase in densities. An

explanation for this may be that only a small amount of quartz cement, which will not cause a marked volume reduction, may have the potential to stiffen the rock framework, thus increasing the velocities.

- From the onset of chemical compaction there is a strong correlation between petrophysical properties and the amounts of quartz cement found by the petrographic analysis. This strong dependency of quartz cement on velocities and densities, and the fact that these properties deviates from the experimental compaction curves at burial depths greater than 2000 meters, indicate that the compaction is a function of temperature insensitive to the effective stress after the onset of chemical compaction. Furthermore, the petrographic analysis showed no evidence of a reduction in intergranular volume after the onset of chemical compaction, which indicates that the source of quartz cementation is from dissolution at stylolites.

Paper 5

Mineralogical control on mudstone compaction: a study of Late Cretaceous to Early Tertiary mudstones of the Vøring and Møre basins, Norwegian Sea (Petroleum Geoscience).

Petrophysical properties from well logs together with more than 300 cutting samples from five wells located in the Møre and Vøring basins offshore mid-Norway was analyzed. The cuttings samples were analyzed with X-Ray Diffraction (XRD) with respect to both whole-rock (bulk) and clay mineralogy. In addition, chemical analysis using X-ray fluorescence (XRF) was used for chemical analysis for one well (6505/10-1) together with scanning electron microscopy (SEM) with energy dispersive X-ray spectroscopy (EDS) to study the chemical composition of feldspars. Results from the mineralogical and chemical analysis showed large compositional variations both as a function of burial depth and the geographical position within the basins. The purpose of this study was to identify and relate the changes in mineralogical content to the compaction trends observed from petrophysical well log data.

Detailed studies of mudstones are sparse in the literature and this paper provides one of the most comprehensive datasets on how variations in mineralogy affect the physical properties in fine-grained sediments. Earlier studies have claimed that grain-size is the main factor influencing the compaction of mudstones (e.g. Aplin et al., 1995), but the data presented in this paper clearly shows the importance on primary clay mineralogy composition as a controlling factor for compaction trends in mudstones. The amount of smectite is especially important for the development of physical properties with depth/temperature.

The main findings and conclusions were:

- Variations in compaction trends for Late Cretaceous to Early Tertiary mudstones in the Vøring and Møre basins as observed from well logs reflect significant changes in the mineralogical compositions.
- The clay mineralogical assemblage of the studied mudstones consists of smectite, illite-smectite (I/S), illite, kaolinite and chlorite. Smectite is the dominant clay mineral in the Cenozoic succession and has a strong influence on velocities and densities.
- The Early Tertiary mudstones in the study area have a decreasing smectite content from south to north. This change is observed in well logs by an increase in both densities and velocities in a northerly direction. An inversion in these properties with depth is seen for the southernmost wells with smectite content up to 50% of the bulk rock volume.
- The clay mineralogical data also show a decrease in smectite with increasing burial depth which may partly be due to thermal alteration of smectite to illite and chlorite. This diagenetic change is observed by the well logs as an increase in both velocity and density in all of the studied wells. A change in primary mineralogical composition evident from a change in the plagioclase/K-feldspar ratio at the Cretaceous-Tertiary boundary may also contribute to this change in physical properties.
- The mineralogical and petrophysical data presented in this paper clearly demonstrate the influence on primary mineralogical composition on compaction trends in mudstones. These changes provide important information that may be used in seismic interpretation and as input for basin modeling to better understand the evolution of a sedimentary basin through time.

Paper 6

Clay mineral diagenesis and quartz cementation in mudstones: The effects of smectite to illite reaction on rock properties (in press – Marine and Petroleum Geology).

Borehole petrophysical well logs and 319 cutting samples from five deep-water wells in the Vøring and Møre basins in the Norwegian Sea were analyzed to study the relationship between sediment composition, diagenesis and physical properties of mudstones. Whole-rock and clay fraction (< 2μm) was analyzed using XRD, in addition major elements were analyzed using XRF and SEM was used to study the samples. Results from the mineralogical and chemical analyses were used together with petrophysical properties from well logs to study the effect of chemical compaction on physical properties.

Special emphasis in this study was on how physical properties change in relation to the smectite to illite reaction (S-I). Significant amounts of silica is released during this clay mineral reaction (Weaver, 1959; Towe, 1962; Boles and Franks, 1979; Srodon, 1999), but there is little evidence on what happens to the silica in the literature. A common assumption has been that the released silica in clay mineral reactions is transported from mudstones and precipitates in associated sandstones (e.g. Hower et al., 1976; Boles and Franks, 1979; Van der Kamp, 2008). However, recent studies (Thyberg et al., 2009) and results from this study indicate that the micro-quartz derived from the smectite to illite reaction is precipitated within the fine-grained clay matrix in mudstones. In order to isolate the effect due to this reaction an interval with relatively constant sediment composition in well 6505/10-1 was chosen for more detailed investigations.

The main findings and conclusions were:

- Analysis of well logs and cutting samples from 5 wells demonstrates that the primary mineralogical composition is the most important factor in determining the chemical compaction of mudstones.
- Results from experimental compaction of clay minerals are in good agreement with the petrophysical properties from well logs in shallow sediments buried to less than about 2000 meter (~70˚C). At greater depths and temperatures, velocities and densities are higher than what is found in the experimental work indicating significant chemical compaction.
- Mineralogical results show that illitization of smectite occurs from depths corresponding to 60-80˚C that results in a release of silica. The mineralogical analysis indicates that the silica remains within the system as locally precipitated quartz. Authigenic micro-quartz found within the clay matrix for the same depth interval identified by SEM and Cathode luminescence (CL) supports this interpretation.
- The presence of authigenic quartz cement within the clay matrix corresponds to marked increase in velocities (V_p and V_s) without a corresponding increase in bulk density. The precipitation of quartz in the micro-porosity of the clay matrix together with the

collapse of smectite from the S-I reaction may have lead to significant stiffening of the clay mineral framework which would result in an increase in velocities.

- At depths corresponding to 60-80˚C the physical properties of mudstones are controlled by chemical compaction, which is mostly sensitive to temperatures. However, the potential for authigenic quartz cementation is dependent on the amounts of unstable silicate minerals such as smectite and amorphous silica present in the mudstone. More stable clay minerals such as kaolinite will be little influenced by chemical compaction than smectite-rich mudstones at temperatures below 130˚C.

General Conclusions

Results from this study document that compaction trends in siliceous sediments may vary significantly depending on the initial mineralogical composition controlled by provenance, depositional environment and burial history of the basin. The combination of petrophysical data from well logs with detailed analysis of the mineralogical and chemical composition of the sediments, petrographic studies, experimental compaction and depositional models have proven to be a good basis for quantifying changes in physical properties in terms of geological processes. It is evident that the amount of smectite in mudstones from the Norwegian continental shelf is the most important factor controlling the mechanical compaction as observed from the compaction trends in well logs. A bulk smectite content of more than about 20% seems to be sufficient to dominate the physical properties in these sediments. Low velocities and densities and high porosities observed within smectite-rich mudstones may deviate greatly from standard compaction trends normally applied to shales. This may be explained by the low compressibility of smectite and by the fact that reduced permeabilities in these sediments may cause increased pore pressures. The presence of smectite also plays an import role for the diagenetic evolution in mudstone as a precursor for diagenetic illite and chlorite and as a source for quartz cement.

This study has also shown that the velocity and density will always increase with increasing burial when a single well defined lithology is studied. The inversion in physical properties with depth presented in this study correlates with changing lithologies.

Early compaction of a relatively clean quartz-rich sandstones is controlled by the vertical effective stress and experimental compaction can be used to describe velocities and porosities with depth. From an excellent correlation between the amounts of quartz cement and bulk density it is evident that chemical compaction (quartz cementation) becomes the main porosity reducing agent as temperatures are increasing during progressive burial.

The implications of various mudstone compaction trends for basin modeling proved to be significant. Modeling of basin geometries, subsidence, heat flow, temperature and hydrocarbon maturation are influenced by the variations in porosity/depth trends for mudstones. The results from this study show that mudstones are very heterogeneous and this clearly affects results obtained from basin modeling.

Physical properties in mudstones acting as cap-rocks for hydrocarbon reservoirs have significant implications for the interpretation of AVO attributes. By varying the cap-rock properties from values resembling a smectite-rich mudstone to a kaolinite-rich mudstone the AVO response of a gas-filled sandstone reservoir changed from a class I to a class II AVO sand. Thus, a sand with identical elastic properties may be interpreted in several ways depending on the physical properties within the overlying cap-rock. With the application of geological models it is possible to extract information about how the physical properties vary within a basin. This will improve the interpretation and classification of AVO attributes.

References

Al-Chalabi, M., 1997. Instantaneous slowness versus depth functions. Geophysics, 62 (1), pp. 270-273.

Allan, P.A., Allan, J.R., 2005. Basin Analysis; Principles and Applications. Blackwell Publishing Ltd, 549 pp.

Aplin, A.C., Yang, Y., Hansen, S., 1995. Assessment of β, the compression coefficient of mudstones and its relationship with detailed lithology. Marine and Petroleum Geology, 12 (8), pp. 955-963.

Athy, L.F., 1930. Density, porosity, and compaction of sedimentary rocks. AAPG Bulletin, 14 (1), pp. 1-24.

Atkins, J.E., McBride, E.F., 1992. Porosity and packing of holocene river, dune, and beach sands. AAPG Bulletin, 76, pp. 339-355.

Avseth, P., Dvorkin, J., Mavko, G., Rykkje, J., 2000. Rock physics diagnostic of North Sea sands; Link between microstructure and seismic properties. Geophysical Research Letters, 27 (17), pp. 2761-2764.

Avseth, P., Mukerji, T., Mavko, G., 2005. Quantitative Seismic Interpretation. Applying Rock Physics Tools to Reduce Interpretation Risk. Cambridge University Press, Cambridge, 359 pp.

Baldwin, B., Butler, C.O., 1985. Compaction curves. AAPG Bulletin, 69 (4), pp. 622-626.

Barker, C., 1972. Aquathermal Pressuring - Role of Temperature in Development of Abnormal-Pressure Zones. AAPG Bulletin, 56 (10), pp. 2068-2071.

Bernabé, Y., Fryer, D.T., Hayes, J.A., 1992. The effect of cement on the strength of granular rocks. Geophysical Research Letters, 19 (14), pp. 1511-1514.

Berstad, S., Dypvik, H., 1982. Sedimentological evolution and natural radioactivity of Tertiary sediments from the Central North Sea. Journal of Petroelum Geology, 5 (1), pp. 77-88.

Bethke, C.M., 1985. A numerical model of compaction-driven groundwater flow and heat transfer and its application to the paleohydrology of intracratonic sedimentary basins. Journal of Geophysical Research, 90 (B2), pp. 6817-6828.

Biot, M.A., 1955. Theory of Propagation of Elastic Waves in a Fluid-Saturated porous Solid. I. Low-frequency Range. The Journal of the Acoustical Society of America, 25 (2), pp, 168-178.

Bjørkum, P.A., 1996. How important is pressure in causing dissolution of quartz in sandstones? Journal of Sedimentary Research, 66 (1), pp. 147-154.

Bjørkum, P.A., Nadeau, P.H., 1998. Temperature Controlled Porosity/Permeability Reduction, Fluid Migration, and Petroleum Exploration in Sedimentary Basins. APPEA Journal, 38 (1), pp. 453-464.

Bjørkum, P.A., Oelkers, E.H., Nadeau, P.H., Walderhaug, O., Murphy, W.M., 1998. Porosity prediction in quartzose sandstones as a function of time, temperature, depth, stylolite frequency, and hydrocarbon stauration. AAPG Bulletin, 82, pp. 637-648.

Bjørlykke, K., 1998. Clay mineral diagenesis in sedimentary basins - a key to the prediction of rock properties. Examples from the North Sea Basin. Clay minerals, 33, pp. 15-34.

Bjørlykke, K., 1999. Principal aspects of compaction and fluid flow in mudstones. In: Aplin, A.C., Fleet, A.J., Macquaker, J.H.S. (Eds.), Muds and Mudstones: Physical and Fluid Flow Properties. The Geological Society (London) Special Publications, 158, pp. 73-78.

Bjørlykke, K., 2006. Effects of compaction processes on stresses, faults, and fluid flow in sedimentary basins: examples from the Norwegian margin. In: Buiter, S.J., Schreurs, G. (Eds.), Analogue and Numerical Modelling of Crustal-Scale processes. The Geological Society (London) Special Publications, 253, pp. 359-379.

Bjørlykke, K., Høeg, K., 1997. Effects of burial diagenesis on stresses, compaction and fluid flow in sedimentary basins. Marine and Petroleum Geology, 14 (3), pp. 267-276.

Bjørlykke, K., Ramm, M., Saigal, G.C., 1989. Sandstone diagenesis and porosity modification during basin evolution. Geologische Rundschau, 78, pp. 243-268.

Bjørlykke, K., Aagaard, P., Dypvik, H., Hastings, D.S., Harper, A.S., 1986. Diagenesis and reservoir properties of Jurassic sandstones from the Haltenbanken area, offshore mid Norway. In: Spencer, A.M. (Ed.), Habitat of hydrocarbons on the Norwegian continental shelf; proceedings of an international conference. Graham & Trotman, London, United Kingdom, pp. 275-286.

Boggs, S., Jr, 1995. Principles of sedimentology and stratigraphy, 2nd edition. Prentice-Hall, Upper Saddle River, New Jersey, 774 pp.

Boles, J.R., Franks, S.G., 1979. Clay diagenesis in Wilcox sandstones of southwest Texas: implications of smectite diagenesis on sandstone cementation. Journal of Sedimentary Petrology, 49, pp. 55-70.

Bredehoeft, J.D., Hanshaw, B.B., 1968. On the Maintenance of Anomalous Fluid Pressures: 1. Thick Sedimentary Sequences. Geological Society of America Bulletin, 79, pp. 1097-1106.

Bruce, C.H., 1984. Smectite Dehydration - Its Relation to Structural Development and Hydrocarbon Accumulation in Northern Gulf of Mexico Basin. AAPG Bulletin, 68 (6), pp. 673-683.

Bulat, J., Stoker, S.J., 1987. Uplift determination from interval velocity studies, UK, southern North Sea. In: Brooks, J., Glennie, K. (Eds.), Petroleum Geology of North West Europe. Graham & Trotman, London, United Kingdom, pp. 293-305.

Castagna, J.P., 1993. Petrophysical imaging using AVO. The Leading Edge, 12, pp. 172-178.

Chilingar, G.V., Knight, L., 1960. Relationship between pressure and moisture content of kaolinite, illite, and montmorillonite clays. AAPG Bulletin, 44 (1), pp. 101-106.

Christiansson, P., Faleide, J.I., Berge, A.M., 2000. Crustal structure in the northern North Sea: an integrated geophysical study. In: Nøttvedt, A. (Ed.), Dynamics of the Norwegian Margin. The Geological Society (London) Special Publications, 167, pp. 15-40.

Chuhan, F.A., Kjeldstad, A., Bjørlykke, K., Hoeg, K., 2002. Porosity loss in sand by grain crushing - experimental evidence and relevance to reservoir quality. Marine and Petroleum Geology, 19 (1), pp. 39-53.

Chuhan, F.A., Kjeldstad, A., Bjørlykke, K., Hoeg, K., 2003. Experimental compression of loose sands; relevance to porosity reduction during burial in sedimentary basins. Canadian Geotechnical Journal, 40 (5), pp. 995-1011.

Densley, M.R., Hillis, R.R., Redfearn, J.E.P., 2000. Quantification of uplift in the Carnarvon Basin based on interval velocities. Australian Journal of Earth Sciences, 47 (1), pp. 111-122.

Deming, D., Chapman, D.S., 1989. Thermal histories and hydrocarbon generation: example from Utah-Wyoming Thrust Belt. AAPG Bulletin, 73 (12), pp. 1455-1471.

Dickinson, G., 1953. Geological aspects of abnormal reservoir pressures in Gulf Coast Louisiana. AAPG Bulletin, 37 (2), pp. 410-432.

Dickinson, W.R., Beard, L.S., Brakenridge, G.R., Erjavec, L.L., Ferguson, R.C., Inman, K.F., Knepp, R.A., Lindberg, F.A., Rykberg, P.T., 1983. Provenance of North American Phanerozoic sandstones in relation to tectonic setting. Geological Society of America Bulletin, 94, pp. 222-235.

Dvorkin, J., Gutierrez, M., 2002. Grain sorting, porosity, and elasticity. Petrophysics, 43, pp. 185-196.

Dvorkin, J., Nur, A., 1996. Elasticity of high-porosity sandstones; Theory for two North Sea datasets. Geophysics, 61 (5), pp. 1363-1370.

Dvorkin, J., Nur, A., Yin, H., 1994. Effective properties of cemented granular material. Mechanics of Materials, 18, pp. 351-366.

Ehrenberg, S.N., 1990. Relationship between diagenesis and reservoir quality in sandstones of the Garn Formation, Haltenbanken, mid-Norwegian continental shelf. AAPG Bulletin, 74 (10), pp. 1538-1558.

Ehrenberg, S.N., Nadeau, P.H., 1989. Formation of diagenetic illite in sandstones of the Garn Formation, Haltenbanken area, Mid-Norwegian Continental shelf. Clay minerals, 24, pp. 233-253.

Faleide, J.I., Kyrkjebø, R., Kjennerud, T., Gabrielsen, R.H., Jordt, H., Fanavoll, S., Bjerke, M.D., 2002. Tectonic impact on sedimentary processes during Cenozoic evolution of the northern North Sea and surrounding areas. In: Doré, A.G., Cartwright, J.A., Stoker, S.J., Turner, J.P., White, N. (Eds.), Exhumation of the North Atlantic Margin; Timing, Mechanisms and Implications for Petroleum Exploration. The Geological Society (London) Special Publications, 196, pp. 235-269.

Fjeldskaar, W., Johansen, H., Dodd, T.A., Thompson, M., 2003. Temperature and Maturity Effects of Magmatic Underplating in the Gjallar Ridge, Norwegian Sea. In: Düppenbecker, S., Marzi, R. (Eds.), Multidimensional basin modeling. AAPG/Datapages Discovery Series 7, pp. 71-85.

Fjeldskaar, W., Prestholm, E., Guargena, C., Gravdal, N., 1993. Isostatic and tectonic subsidence of the Egersund Basin. In: Doré, A.G., Augustson, J.H., Hermanrud, C., Stewart, D.J., Sylta, Ø. (Eds.), Basin Modelling: Advances and Applications. Norwegian Petroleum Society (NPF), Special Publication 3, pp. 549-562.

Fjeldskaar, W., Voorde, M.t., Johansen, H., Christiansson, P., Faleide, J.I., Cloeting, S.A.P.L., 2004. Numerical simulation of rifting in the northern Viking Graben: the mutual effect of modelling parameters. Tectonophysics, 382, pp. 189-212.

Foster, J.B., Whalen, H.E., 1966. Estimation of formation pressures from electrical surveys - offshore Louisiana. Journal of Petroleum Technology, 18 (2), pp. 165-171.

Galloway, W.E., 1984. Hydrogeologic regimes of sandstone diagenesis. In: MacDonald, D.A., Surdam, R.C. (Eds.), Clastic Diagenesis. AAPG Memoir, 37, pp. 3-14.

Gardner, G.H.F., Gardner, L.W., Gregory, A.R., 1974. Formation velocity and density; the diagnostic basics for stratigraphic traps. Geophysics, 39 (6), pp. 770-780.

Gassmann, F., 1951. Elastic waves through a packing of spheres. Geophysics, 16 (4), pp. 673-685.

Gibbs, R.J., 1977. Clay mineral segregation in the marine environment. Journal of Sedimentary Petrology, 47 (1), pp. 237-243.

Giles, M.R., 1997. Diagenesis: A Quantitative Perspective. Implications for Basin Modelling and Rock Property Prediction. Kluwer Academic Publishers, Dordrecht, 526 pp.

Giles, M.R., Stevenson, S., Martin, S.V., Cannon, S.J.C., Hamilton, P.J., Marshall, J.D., Samways, G.M., 1992. The reservoir properties and diagenesis of the Brent Group:

a regional perspective. In: Morton, A.C., Haszeldine, R.S., Giles, M.R., Brown, S. (Eds.), Geology of the Brent Group. The Geological Society (London) Special Publication, 61, pp. 289-327.

Hammond, A.L., 1974. Bright Spot: Better Seismological Indiactors of Gas and Oil. Science, 185 (4150), pp. 515-517.

Han, D.h., Nur, A., Morgan, D., 1986. Effects of porosity and clay content on wave velocities in sandstones. Geophysics, 51 (11), pp. 2093-2107.

Hansen, S., 1996a. Quantification of net uplift and erosion on the Norwegian Shelf south of 66 degrees N from sonic transit times of shale. Norsk Geologisk Tidsskrift, 76 (4), pp. 245-252.

Hansen, S., 1996b. A compaction trend for Cretaceous and Tertiary shales on the Norwegian Shelf based on sonic transit times. Petroleum Geoscience, 2 (2), pp. 159-166.

Ham, H.H., 1966. New charts help estimate formation pressures. The Oil and Gas Journal, 65 (51), pp. 58-63.

Hedberg, H.D., 1936. Gravitational compaction of clays and shales. American Journal of Science, 31 (184), pp. 241-287.

Hashin, Z., Shtrikman, S., 1963. A variational approach to the elastic behavior of multiphase materials. Journal of Mech. Phys. Solids, 11, pp. 127-140.

Hendrie, D.B., Kusznir, N.J., Hunter, R.H., 1993. Jurassic extension estimates for the North Sea 'triple junction' from flexural backstripping: implications for decompression melting models. Earth Planetary Science Letters, 116, pp. 113-127.

Hermanrud, C., 1993. Basin modelling techniques - an overview. In: Doré, A.G., Augustson, J.H., Hermanrud, C., Stewart, D.J., Sylta, Ø. (Eds.), Basin Modelling: Advances and Applications. Norwegian Petroleum Society (NPF), Special Publication 3, pp. 1-34.

Hermanrud, C., Wensaas, L., Teige, G.M.G., Nordgård Bolås, H.M., Hansen, S., Vik, E., 1998. Shale porosities from well logs on Haltenbanken (offshore mid-Norway) show no influence of overpressuring. In: Law, B.E., Ulmishek, G.F., Slavin, A.I. (Eds.), Abnormal pressures in hydrocarbon environments. American Association of Petroleum Geologists, Tulsa, OK, United States 70; , pp. 65-85.

Herring, E.A., 1973. North Sea Abnormal Pressures Determined From Logs. Petroleum Engineer, November, pp. 72-84.

Hillis, R.R., 1995. Quantification of Tertiary Exhumation in the United Kingdom Southern North Sea Using Sonic Velocity Data. AAPG Bulletin, 79 (1), pp. 130-152.

Hosoi, H., 1963. First migration of petroleum in Akita and Yamagata Prefectures. Jap. Assoc. Mineralogists, 49 (2), pp. 43-55.

Hottmann, C.E., Johnson, R.K., 1965. Estimation of formation pressures from log-derived shale properties. Journal of Petroleum Technology, 17, pp. 717-723.

Hower, J., Eslinger, E.V., Hower, M.E., Perry, E.A., 1976. Mechanism of burial metamorphism of argillaceous sediment: Mineralogical and chemical evidence. Geological Society of America Bulletin, 87, pp. 725-737.

Huggett, J.M., Knox, R.W.O.B., 2006. Clay mineralogy of the Tertiary onshore and offshore strata of the British Isles. Clay Minerals, 41, pp. 5-46.

Hurst, A.R., 1985. Diagenetic chlorite formation in some Mesozoic shales from the Sleipner area of the North Sea. Clay Minerals, 20 (1), pp. 69-79.

Japsen, P., 1999. Overpressured Cenozoic shale mapped from velocity anomalies relative to a baseline for marine shale, North Sea. Petroleum Geoscience, 5 (4), pp. 321-336.

Jordt, H., Faleide, J.I., Bjørlykke, K., Ibrahim, M.T., 1995. Cenozoic sequence stratigraphy of the central and northern North Sea Basin: tectonic development, sediment distribution and provenance areas. Marine and Petroleum Geology, 12 (8), pp. 845-879.

Jordt, H., Thyberg, B.I., Nøttvedt, A., 2000. Cenozoic evolution of the central and northern North Sea with focus on differential vertical movements of the basin floor and surrounding clastic source areas. In: Nøttvedt, A. (Ed.), Dynamics of the Norwegian margin. The Geological Society (London) Special Publications, 167, pp. 219-243.

Karlsson, W., Vollset, J., Bjørlykke, K., Jørgensen, P., 1979. Changes in mineralogical composition of Tertiary sediments from North Sea wells. In: Mortland, M.M., Farmer, V.C. (Eds.), International Clay Conference 1978, Developments in Sedimentology 27. Proceedings of the VI International Clay Conference 1978, pp. 281-289.

Kusznir, N.J., Roberts, A.M., Morley, C.K., 1995. Forward and reverse modeling of rift basin formation. In: Lambiase, J.J. (Ed.), Hydrocarbon Habitat in Rift Basins. The Geological Society (London) Special Publications, 80, pp. 33-56.

Kyrkjebø, R., 1999. The Cretaceous - Tertiary of the northern North Sea: thermal and tectonic influences in a post-rift setting. Doctor Scientiarum Thesis, University of Bergen.

Magara, K., 1968. Compaction and migration of fluids in Miocene mudstone, Nagaoka plain, Japan. AAPG Bulletin, 52 (12), pp. 2466-2502.

Marine, I.W., Fritz, S.J., 1981. Osmotic Model to Explain Anomalous Hydraulic Heads. Water Resources Research, 17 (1), pp. 73-82.

Marion, D., Nur, A., Yin, H., Han, D., 1992. Compressional velocity and porosity in sand-clay mixtures. Geophysics, 57 (4), pp. 554-563.

Meade, R.H., 1966, Factors influencing the early stages of the compaction of clays and sands - review. Journal of Sedimentary Petrology, 36 (4), pp. 1085-1101.

Mindlin, R.D., 1949. Compliance of elastic bodies in contact. Journal of applied Mechanics, 16, pp. 259-268.

Mitchum, R.M., 1977. Seismic Stratigraphy and Global Changes of Sea Level, Part 11: Glossary of Terms used in Seismic Stratigraphy. In: Payton, C.E. (Ed.), Seismic startigraphy - Applications to Hydrocarbon Exploration. AAPG Memoir, 26, pp. 205-212.

Mitchum, R.M., Vail, P.R., Sangree, J.B., 1977a. Seismic Stratigraphy and Global Changes of Sea Level, Part 6: Stratigraphic Interpretation of Seismic Reflection Patterns in Depositional Sequences. In: Payton, C.E. (Ed.), Seismic Stratigraphy - Applications to Hydrocarbon Exploration. AAPG Memoir, 26, pp. 117-133.

Mitchum, R.M., Vail, P.R., Thompson, S., 1977b. Seismic Stratigraphy and Global Changes of Sea Level, Part 2: The Depositional Sequence as a Basic Unit for Stratigraphic Analysis. In: Payton, C.E. (Ed.), Seismic Stratigraphy - Applications to Hydrocarbon Exploration. AAPG Memoir, 26, pp. 53-62.

Mondol, N.H., 2007. Experimental and natural compaction of mudstones, Ph.D. Thesis, University of Oslo.

Mondol, N.H., Bjørlykke, K., Jahren, J., 2008a. Experimental compaction of clays: relationship between permeability and petrophysical properties in mudstones. Petroleum Geoscience, 14, pp. 1-19.

Mondol, N.H., Bjørlykke, K., Jahren, J., Hoeg, K., 2007. Experimental mechanical compaction of clay mineral aggregates - Changes in physical properties of mudstones during burial. Marine and Petroleum Geology, 24 (5), pp. 289-311.

Mondol, N.H., Fawad, M., Jahren, J., Bjørlykke, K., 2008b. Synthetic mudstone compaction trends and their use in pore pressure prediction. First Break, 26, pp. 43-51.

Murphy, W.M., Oelkers, E.H., Lichtner, P.C., 1989. Surface reaction versus diffusion control of mineral dissolution and growth rates in geochemical processes, Kinetic geochemistry. Elsevier, Amsterdam, Netherlands, 78; 3-4, pp. 357-380.

Nadeau, P.H., Peacor, D.R., Yan, J., Hillier, S., 2002. I-S precipitation in pore space as the cause of geopressuring in Mesozoic mudstones, Egersund Basin, Norwegian continental shelf. American Mineralogist, 87, pp. 1580-1589.

Nadin, P.A., Kusznir, N.J., 1995. Palaeocene uplift and Eocene subsidence in the northern North Sea Basin from 2D forward and reverse stratigraphic modelling. Journal of the Geological Society (London), 152, pp. 833-848.

Nafe, J.E., Drake, C.L., 1957. Variation with depth in shallow and deep water marine sediments of porosity, density and the velocities of compressional and shear waves. Geophysics, 22 (3), pp. 523-552.

Nygård, R., Gutierrez, M., Høeg, K., Bjørlykke, K., 2004. Influence of burial history on microstructure and compaction behaviour of Kimmeridge Clay. Petroleum Geoscience, 10 (3), pp. 259-270.

Odinsen, T., Christiansson, P., Gabrielsen, R.H., Faleide, J.I., Berge, A.M., 2000a. The geometries and deep structure of the northern North Sea rift system. In: Nøttvedt, A. (Ed.), Dynamics of the Norwegian Margin. The Geological Society (London) Special Publications, 167, pp. 41-57.

Odinsen, T., Reemst, P., van der Beek, P., Faleide, J.I., Gabrielsen, R.H., 2000b. Permo-Triassic and Jurassic extension in the northern North Sea: results from tectonostratigraphic forward modeling. In: Nøttvedt, A. (Ed.), Dynamics of the Norwegian margin. The Geological Society (London) Special Publications, 167, pp. 83-103.

Oelkers, E.H., Bjørkum, P.A., Murphy, W.M., 1992. The mechanism of porosity reduction, stylolite development and quartz cementation in North Sea sandstones. In: Kharaka, Y.K., Maest, A.S. (Eds.), Water-rock interaction. Rotterdam, Balkema, 2, pp. 1183-1186.

Oelkers, E.H., Bjørkum, P.A., Murphy, W.M., 1993. Calculation of the rate and distribution of chemically driven quartz cementation in North Sea sandstones. In: Cuney, M., Cathelineau, M. (Eds.), Proceedings of the Fourth International Symposium on Hydrothermal Reactions. Institute Lorain des Geosciences, Nancy, pp. 169-172.

Oelkers, E.H., Bjørkum, P.A., Murphy, W.M., 1996. A Petrographic and computational investigation of quartz cementation and porosity reduction in North Sea sandstones. American Journal of Science, 296, pp. 420-452.

Ostrander, W.J., 1984. Plane-wave reflection coefficients for gas sands at nonnormal angles of incidence. Geophysics, 49 (10), pp. 1637-1648.

Pearson, M.J., 1990. Clay mineral distribution and provenance in Mesozoic and Tertiary mudrocks of the Moray Firth and northern North Sea. Clay Minerals, 25 (4), pp. 519-541.

Pearson, M.J., Small, J.S., 1988. Illite-smectite diagenesis and palaeotemperatures in northern North Sea Quarternary to Mesozoic shale sequences. Clay Minerals, 23 (2), pp. 109-132.

Peltonen, C.B., Marcussen, Ø., Bjørlykke, K., Jahren, J., 2008. Mineralogical control on mudstone compaction: a study of Late Cretaceous to Early Tertiary mudstones of the Vøring and Møre Basins, Norwegian Sea. Petroleum Geoscience, 14, pp. 127-138.

Pennebaker, E.S., 1968. Seismic data indicate depth and magnitude of abnormal pressure. World Oil, 166, pp. 73-82.

Potter, P.E., Maynard, J.B., Depetris, P.J., 2005. Mud and Mudstones. Springer, New York, 297 pp.

Powers, M.C., 1967. Fluid-release mechanisms in compacting marine mudrocks and their importance in oil exploration. AAPG Bulletin, 51 (7), pp. 1240-1254.

Primmer, T.J., Shaw, N.D., 1987. Diagenesis in shales; evidence from backscattered electron microscopy and electron microprobe analysis. Proceedings of the International clay conference, pp. 135-143.

Ramm, M., 1992. Porosity-depth trends in reservoir sandstones; theoretical models related to Jurassic sandstones offshore Norway. Marine and Petroleum Geology, 9 (5), pp. 553-567.

Ramm, M., Bjørlykke, K., 1994. Porosity/depth trends in reservoir sandstones; assessing the quantitative effects of varying pore-pressure, temperature history and mineralogy, Norwegian Shelf data. Clay Minerals, 29 (4), pp. 475-490.

Reemst, P., Skogseid, J., Larsen, B.T., 1996. Base Pliocene velocity inversion on the eastern Vøring Margin - causes and implications. Global and Planetary Change, 12, pp. 201-211.

Reuss, A., 1929. Berechnung der Fliessgrenzen von Mischkristallen. Z. Angew. Math. Mech., 9, pp. 49-58.

Reynolds, E.B., 1970. Predicting overpressured zones with seismic data. World Oil, 171, pp. 78-82.

Roberts, A.M., Kusznir, N.J., Yielding, G., Styles, P., 1998. 2D flexural backstripping of extensional basins: the need for a sideways glance. Petroleum Geoscience, 4, pp. 327-338.

Rundberg, Y., 1989. Tertiary sedimentary history and basin evolution of the Norwegian North Sea between 60°N and 62°N. An integrated approach. Ph.D. Thesis, University of Trondheim.

Rüpke, L.H., Schmalholz, S.M., Schmid, D.W., Podladchikov, Y.Y., 2008. Automated thermotectonostratigraphic basin reconstruction: Viking Graben case study. AAPG Bulletin, 92 (3), pp. 309-326.

Scherer, M., 1987. Parameters influencing porosity in sandstones: a model for sandstone porosity prediction. AAPG Bulletin, 71 (5), pp. 485-491.

Schieber, J., Zimmerle, W., 1998. Introduction and Overview: The History and Promise of Shale Research. In: Schieber, J., Zimmerle, W., Sethi, P.V. (Eds.), Shales and Mudstones (Volume I): Basin Studies, Sedimentology and Paleontology. E.

Schweizerbart'sche Verlagsbuchhandlung (Nägele i. Obermiller), Stuttgart, pp. 1-10.

Sclater, J.G., Christie, P.A.F., 1980. Continental stretching: An explanation of the post-mid-Cretaceous subsidence of the central North Sea Basin. Journal of Geophysical Research, 85 (B7), pp. 3711-3739.

Schmoker, J.W., Gautier, D.L., 1988. Sandstone porosity as a function of thermal maturity. Geology, 16, pp. 1007-1010.

Srodon, J., 1999. Nature of mixed-layer clays and mechanisms of their formation and alteration. Annual Review of Earth and Planetary Sciences, 27, pp. 19-53.

Steckler, M.S., Watts, A.B., 1978. Subsidence of the Atlantic-type continental margin off New York. Earth Planetary Science Letters, 41, pp. 1-13.

Storvoll, V., Bjørlykke, K., Mondol, N.H., 2005. Velocity-depth trends in Mesozoic and Cenozoic sediments from the Norwegian shelf. AAPG Bulletin, 89 (3), pp. 359-381.

Summa, L.L., 1993. Paleohydrology of the Gulf of Mexico Basin: development of compactional overpressure and timing of hydrocarbon migration relative to cementation. In: Doré, A.G., Augustson, J.H., Hermanrud, C., Stewart, D.J., Sylta, Ø. (Eds.), Basin Modelling: Advances and applications. Norwegian Petroleum Society (NPF), Special Publication, 3, pp. 641-656.

Swarbrick, R.E., Osborne, M.J., 1998. Mechanisms that generate abnormal pressures; an overview. In: Law, B.E., Ulmishek, G.F., Slavin, V.I. (Eds.), Abnormal pressures in hydrocarbon environments. American Association of Petroleum Geologists, Tulsa, OK, United States, pp. 13-34.

Teige, G.M.G., Hermanrud, C., Wensaas, L., M., N.B.H., 2007. Geological constraints of pore pressure detection in shales from seismic data. Basin Research, 19, pp. 33-50.

Thyberg, B.I., Jahren, J., Winje, T., Bjørlykke, K., Faleide, J.I., 2009. From mud to shale: rock stiffening by micro-quartz cementation. First Break, 27, pp. 27-33.

Thyberg, B.I., Jordt, H., Bjørlykke, K., Faleide, J.I., 2000. Relationships between sequence stratigraphy, mineralogy and geochemistry in Cenozoic sediments of the northern North Sea. In: Nøttvedt, A. (Ed.), Dynamics of the Norwegian margin. The Geological Society (London) Special Publications, 167 pp. 245-272.

Towe, K.M., 1962. Clay mineral diagenesis as a possible source of silica cement in sedimentary rocks. Journal of Sedimentary Petrology, 32, pp. 26-28.

Vail, P.R., 1975. Eustatic cycles from seismic data for global stratigraphic analysis. AAPG Bulletin, 59, pp. 2198-2199.

Vail, P.R., 1987. Seismic stratigraphy interpretation using sequence stratigraphy, Part I. Seismic stratigraphy interpretation procedure. In: Bally, A.W. (Ed.), Seismic startigraphy Atlas. American Association of Petroleum Geologists Stud Geol 27, pp. 1-10.

Vail, P.R., Mitchum, R.M., Todd, R.G., Widmier, J.M., Thompson, S., Dangree, J.B., Bubb, J.N., Hatlelid, W.G., 1977. Seismic Stratigraphy and Global Changes of Sea Level. In: Payton, C.E. (Ed.), Seismic startigraphy - Applications to Hydrocarbon Exploration. AAPG Memoir, 26, pp. 49-212.

Vail, P.R., Sangree, J.B., 1971. Time stratigraphy from seismic data. AAPG Bulletin, 55, pp. 367-368.

Van der Kamp, P.C., 2008. Silica diagenesis, I. Solubility controls. Journal of Sedimentary Petrology, 55, pp. 301-311.

van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S., Hardenbol, J., 1988. An overview of the fundamentals of sequence stratigraphy and key definitions. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.S.C., Posamentier, H.W., Ross, C.A., van Wagoner, J.C. (Eds.), Sea-Level changes: An integrated Approach. Soc. Econ. Paleontol. Mineral., Special Publication, 42, pp. 39-45.

Velde, B., 1996. Compaction trends of clay-rich deep sea sediments. Marine Geology, 133, pp. 193-201.

Vernik, L., Nur, A., 1992. Petrophysical Classification of Siliciclastics for Lithology and Porosity Prediction from Seismic Velocities. AAPG Bulletin, 76 (9), pp. 1295-1309.

Voigt, W., 1910. Lehrbuch der Kristallphysik. Teubner, Leipzig.

Walderhaug, O., 1994a. Precipitation rates for quartz cement in sandstones determined by fluid-inclusion microthermometry and temperature-history modeling. Journal of Sedimentary Research, Section A: Sedimentary Petrology and Processes, 64 (2), pp. 324-333.

Walderhaug, O., 1994b. Temperatures of quartz cementation in Jurassic sandstones from the Norwegian continental shelf; evidence from fluid inclusions. Journal of Sedimentary Research, Section A: Sedimentary Petrology and Processes, 64 (2), pp. 311-323.

Walderhaug, O., 1996. Kinetic modeling of quartz cementation and porosity loss in deeply buried sandstone reservoirs. AAPG Bulletin, 80 (5), pp. 731-745.

Walderhaug, O., 2000. Modeling quartz cementation and porosity in Middle Jurassic Brent Group sandstones of the Kvitebjørn Field, northern North Sea. AAPG Bulletin, 84 (9), pp. 1325-1339.

Watts, A.B., Karner, G.D., Steckler, M.S., 1982. Lithospheric flexure and the evolution of sedimentary basins. Philosophical Transactions of the Royal Society London, A305, pp. 249-281.

Watts, A.B., Ryan, W.B.F., 1976. Flexure of the Lithosphere and Continental Margin Basins. Tectonophysics, 36, pp. 25-44.

Weaver, C.E., 1959. The clay petrology of sediments. In: Swineford, A. (Ed.), Clays and Clay Minerals. Pergamon Press, Oxford, pp. 154-187.

Weaver, C.E., 1989. Clays, Muds, and Shales. Elsevier Science Publishers B. V., Amsterdam, 819 pp.

Weller, J.M., 1959. Compaction of sediments. AAPG Bulletin, 43 (2), pp. 273-310.

Winkler, K.W., 1983. Contact stifness in granular porous materials: comparison between theory and experiment. Geophysical Research Letters, 10 (11), pp. 1073-1076.

Wyllie, M.R.J., Gregory, A.R., Gardner, L.W., 1956. Elastic wave velocities in heterogeneous and porous media. Geophysics, 21 (1), pp. 41-70.

Wyllie, M.R.J., Gregory, A.R., Gardner, L.W., 1958. An experimental investigation of factors affecting elastic wave velocities in porous media. Geophysics, 23 (3), pp. 459-493.

Xiao, H.B., Suppe, J., 1989. Role of compaction in listric shape of growth normal faults. AAPG Bulletin, 73 (6), pp. 777-786.

Paper 1

Physical properties of Cenozoic mudstones from the northern North Sea: Impact of clay mineralogy on compaction trends

By:

Øyvind Marcussen, Brit I. Thyberg, Christer Peltonen, Jens Jahren, Knut Bjørlykke and Jan Inge Faleide

AAPG Bulletin

(vol. 93 (1), pp. 127-150)

Paper 2

Mudstone compaction trends in basin modeling: a study of Mesozoic and Cenozoic sediments in the northern North Sea

By:

Øyvind Marcussen, Jan Inge Faleide, Jens Jahren & Knut Bjørlykke

Basin Research

(submitted)

Paper 3

AVO response as a function of cap-rock properties – a case study from the northern North Sea

By:

Øyvind Marcussen, Manzar Fawad, Leiv-J Gelius, Jan Inge Faleide and Isabelle Lecomte

First Break

(submitted)

Paper 4

Changes in physical properties of a reservoir sandstone as a function of burial depth – the Etive Formation, northern North Sea

By:

Øyvind Marcussen, Tom Erik Maast, Nazmul H. Mondol, Jens Jahren and Knut Bjørlykke

Marine and Petroleum Geology

(Submitted)

Paper 5

Mineralogical control on mudstone compaction: a study of Late Cretaceous to Early Tertiary mudstones of the Vøring and Møre basins, Norwegian Sea

By:

Christer Peltonen, Øyvind Marcussen, Knut Bjørlykke and Jens Jahren

Petroleum Geoscience

(vol. 14, 2008, pp. 127-138)

Paper 6

Clay mineral diagenesis and quartz cementation in mudstones: The effects of smectite to illite reaction on rock properties

By:

Christer Peltonen, Øyvind Marcussen, Knut Bjørlykke and Jens Jahren

Marine and Petroleum Geology

(in press)